50 MM SOLID ARMATURE DEVELOPMENT PROGRAM AT THE ELECTRIC ARMAMENTS DIVISION

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Abstract: A solid armature development program is ongoing at the Electric Armaments Division of ARDEC. The program seeks to develop armatures in the 600 KA to 1.0 MA current range using a 5 m x 50 mm composite overwrap style barrel designed by the Benet Weapons Lab. The structural and electrical performance of both novel and conventional armature geometries were characterized in the 500 to 1800 m/s velocity domain. Armatures were engineered to satisfy acceptable design goals of compliance, temperature rise and performance repeatability. The candidate armature geometries, the engineering design rationale which supports them and the test results are presented.

Solid Armature Test Objectives and Apparatus

The test objectives for the solid armature development program were to minimize barrel wear by satisfying both reasonable and achievable levels of armature compliance, conductor temperature rise and to demonstrate performance at these levels in multiple shots. Tests were conducted in the 600 KA to 1.0 MA current range using the 30 MJ/1.3 MA homopolar power supply with its 4µH/3.4 MJ storage inductor. The armatures were launched from a 5 m x 50 mm, copper rail, composite overwrap style barrel. Velocity goals were in the 500 to 1800 m/s range with a launch masses ranging from 200 to 1200 grams.

Engineering Design Rationale

Given the barrel length and bore size, the engineering design rationale identifies the armature parameters which could be varied to meet the test objectives. These armature parameters are as follows:

Mass
Geometry
Contact Normal Force
Material Properties
Cross Sectional Area

Armature Mass: For the 5 meter long barrel, the armature mass and applied current determine the magnitudes of electrical action, velocity and muzzle current level at exit. With the stated goal of minimizing barrel wear, an analysis of exit current as a function of mass was performed. It was determined that for a given peak current, the magnitude of the exit current was essentially independent of mass. However, electrical action and velocity were dependant on the mass. Given the velocity goals, a 200 g to 1200 g mass range was considered acceptable while the minimum armature cross sectional conductor area was sized for the anticipated electrical action.

Armature Geometries: The candidate armature geometries were evaluated based on risk, manufacturability, operational experience, compliance and launch efficiency. Figures 1 and 2 illustrate the two candidates tested to date.

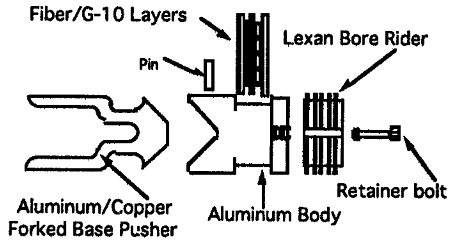

Figure 1
Redundant Armature Metal Base Armature (RAMBO)

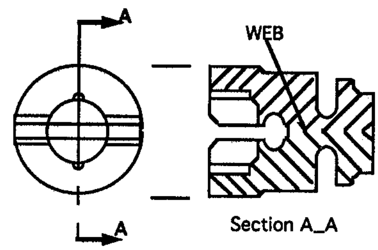

Figure 2
Single Fantail Armature

The RAMBO armature was chosen as a baseline design since it included the fiber armature, a design with which, we have considerable operational and manufacturing experience. A distributed armature approach was chosen to attempt to demonstrate current sharing between the front (fiber) and rear (solid) contacts. The redundant contact geometry was also chosen for the purpose of reliability and safety. Should one armature fail, the other would carry the remaining gun current.

Contact Normal Force and Armature Compliance: The quality of the armature to rail solid contact varies directly with the armatures ability to radially comply with the circular rail. The contact normal force is attributable to the mechanical interference, the armature stiffness, and the induced magnetic normal force associated with the length/separation of the trailing arms. Muzzle voltage is one measure of this overall compliance. The magnitude of the muzzle voltage characterizes the parasitic energy loss associated with the contact quality. A figure of merit was defined to quantify the compliance of the armature contact. The "Armature Quality Factor" was computed by the following:

$$AQF = \frac{E_{KINETIC}}{E_{ELECTRIC}} \cdot 100 \quad (1)$$

where;

$$E_{KINETIC} = \frac{mass \cdot velocity^2}{2} \quad (2)$$

$$E_{ELECTRIC} = \int_0^t MuzzleVoltage \cdot Gun\ Amps\,dt \quad (3)$$

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A solid armature development program is ongoing at the Electric Armaments Division of ARDEC. The program seeks to develop armatures in the 600 KA to 1.0 MA current range using a 5 m x 50 mm composite overwrap style barrel designed by the Benet Weapons Lab. The structural and electrical performance of both novel and conventional armature geometries were characterized in the 500 to 1800 m/s velocity domain. Armatures were engineered to satisfy acceptable design goals of compliance, temperature rise and performance repeatability. The candidate armature geometries, the engineering design rationale which supports them and the test results are presented.</td></tr>
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Comparatively, those armatures with high quality factors were designated as being more compliant than those with low quality factors.

The induced magnetic normal force was calculated using a modified parallel plate force equation to account for narrow trailing arms close together. Equation (4) provides a more accurate representation of the magnitude of the magnetic normal force when compared to the infinite parallel wire formula, $\frac{\mu_0 I^2}{2\pi R}$ [1]. Figure 3 illustrates the the comparative forces.

$$\text{Force(N)} = \frac{\mu_0 I^2}{2\pi a} \text{ArcTan}\frac{a}{2R} \quad (4)$$

where;
R: Trailing Arm Separation Distance (m)
a: Trailing Arm Width (m)

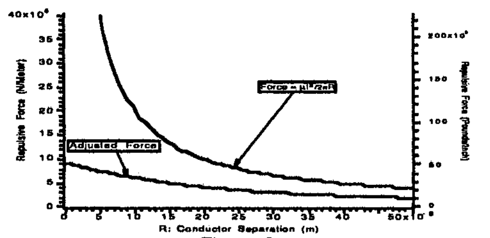

Figure 3
Comparison of Magnetic Repulsive Forces per Unit Length vs Conductor Separation Distance at 1.0 MA
Fixed Conductor Width: a=35mm

The anticipated armature trailing arm deflection was calculated using the closed form cantilever beam equation expressed in (5) below. Static trailing arm compression and expansion deflection tests were performed to confirm the validity of the cantilever beam model and to ensure that the armature was deflecting under load as designed. Figure 4 illustrates the results of the test.

$$\text{Deflection/ Pound of Force} = \frac{4}{E\,b} \cdot \left(\frac{L}{h}\right)^3 \quad \text{(In/lb)} \quad (5)$$

where;
L: Trailing Arm Length (inches)
b: Trailing Arm Width (inches)
h: Trailing Arm Thickness (inches)

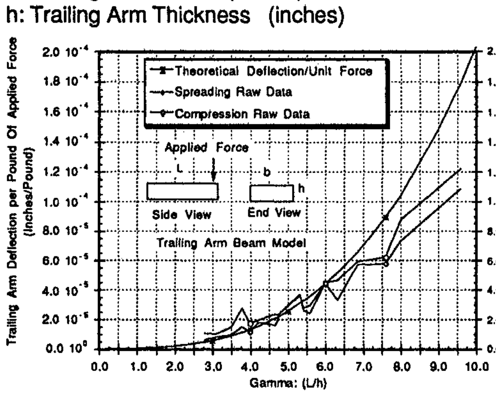

Figure 4
Trailing Arm Deflection Test Results
Deflection vs Applied Force

Based on a .025 in rail deflection at 1.5 MA, the rail deflection at 1.0 MA is .011 in. For L/h = 4.5, the required force to deflect the trailing arm 0.011 inches is 550 lbs. For a 1.75 inch long trailing arm (assuming the current enters at the rear) and a separation of R=35 mm (1.37 in), the repulsive force at 1 MA is 17,500 lb. The net trailing arm normal force is then dominated by the magnetic repulsion force.

Material Properties: The material property of choices were dominated by the need for high yield and tensile strength and high conductivity per unit mass. For this reason, the 7075-T6 and 6061-T6 grades of aluminum and Glidcop-AL60 copper were chosen. The expected temperature rise for the armature was determined from the anticipated specific action as follows:

$$\text{Temp (C)} = (1/\beta)\cdot(1 + \beta T_0)\exp(\beta G/(DCC_0)) - 1) \quad (2)$$

Where:

β: Temperature Coefficient of Resistivity	1/C
G: Specific Action	A^2-s/m^4
D: Density	Kg/m^3
T_0: Room Temperature	C
C_0: Conductivity	1/Ω-cm
C: Specific Heat	J/Kg-C

Figure 5 compares the temperature of the 7075 series aluminum to that of the 6061 series as a function of specific Action. Although the 7075 series of aluminum has double the room temperature yield strength of 6061 aluminum, the 7075 aluminum runs much hotter since it has twice the resistivity. As a result, the elevated temperature of 7075 series aluminum results in a reduction in its yield strength. Future tests will seek to validate the tradeoffs in performance given the temperature and strength differences between the two materials.

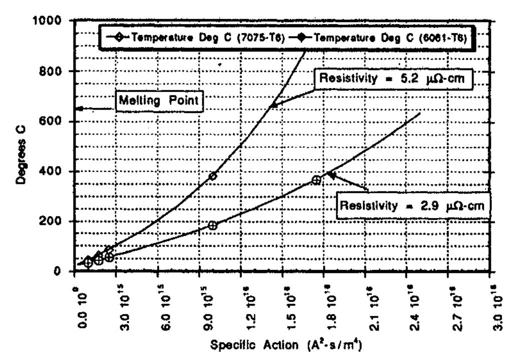

Figure 5
7075 and 6061 Aluminum Temperature vs Specific Action

Cross Sectional Area: The minimum armature cross sectional area is governed by the anticipated specific action and the allowable temperature rise. Applying a 1.5 safety factor to the melting temperature, a 400 °C limit was prescribed. Figure 6 illustrates the allowable specific action at 400°C as a function of conductor cross sectional area for both the 7075 and 6061 series of aluminums.

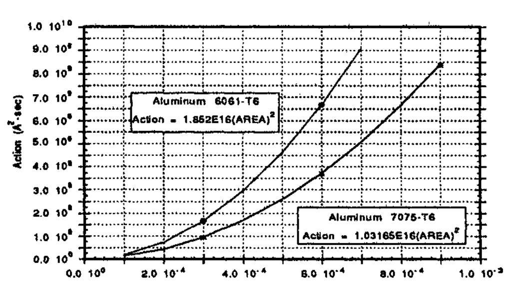

Figure 6
Conductor Cross Sectional Area vs Specific Action at 400 Degrees Centigrade for 7075 and 6061 Aluminum

Testing: As shown in Figure 7, the RAMBO armature tests were conducted as an A/B comparison between 7075 Aluminum and Glidcop-AL60 armature materials. Given the design goals, the minimum web size of the armature was optimized for the expected action.

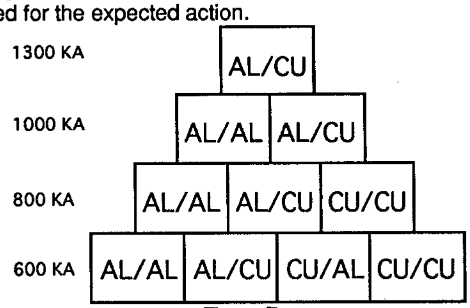

Figure 7
RAMBO Armature Test Matrix
Tail/Fiber

Test Results: The test results are summarized in Table 1, Figures 8 and 9.

Table 1
RAMBO Test Results

Style	Web	Mass	Amps	Action	Velocity
AL/AL	.118"	600g	565KA	2.6E9	554m/s
CU/AL	.118"	894g	447KA	1.0E9	321m/s
AL/CU	.400"	765g	472KA	1.8E9	381m/s
CU/CU	.400"	1124g	480KA	2.1E9	350m/s
AL/AL	.275"	631g	730KA	3.2E9	837m/s
CU/CU	.275"	1215g	880KA	5.0E9	610m/s
AL/CU	.275"	751g	846KA	4.3E9	800m/s
CU/CU	.275"	1145g	1.0MA	3.2E9	900m/s
AL/CU	.375"	754g	890KA	3.4E9	1000m/s

Figure 8 illustrates the required action to begin melting of aluminum and copper as a function of web thickness. When the actual webs and actions from Table 1 are plotted against the aluminum and copper melting curves, the test results fall into three categories.

1. Inadequate web resulting in early melt out, high compliance and low AQF
2. Excessive web resulting in low compliance and low AQF
3. Optimum web resulting in high compliance and high AQF

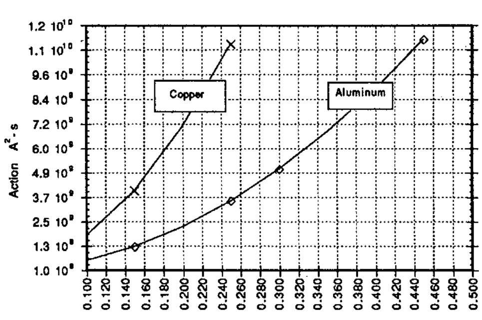

Figure 8
Web Thickness vs Action to Melt

Figure 9 summarizes the RAMBO test results. Level II-800 KA, RAMBO shots 5 and 7 demonstrated the highest values of AQF, therefore, the most compliant.

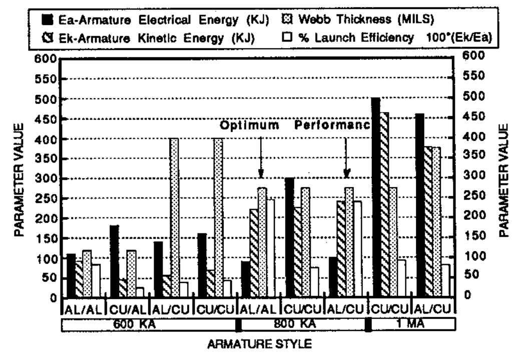

Figure 9
RAMBO Armature Test Results
Web Thickness, Kinetic Energy, Armature Electrical Energy and Armature Quality Factor vs Armature Style

Although the design premise for the redundant armature contacts in the RAMBO was to afford current sharing, a relative distribution of current was not distinguishable in the Bdot traces. Post shot inspection of the armature indicated that current had flowed in the forward fiber body. It is believed that the difference in relative radial stiffness between that of the fiber body and the Fantail sections contributed to forward currents in the armature at start-up. Figure 10 illustrates the probable condition of the contacts at start-up. The stiffer fiber armature would make contact with the rails ahead of the more compliant Fantail armature in the rear. Initially current would flow to the fiber body causing rail separation at the Fantail location. As the fiber armature was consumed by action and wear, the current shifted to the Fantail section. This conclusion is supported by the appearance of the muzzle voltage traces which rise to 70 volts over the first millisecond of the launch then abruptly drops to 10 volts for the duration of the shot.

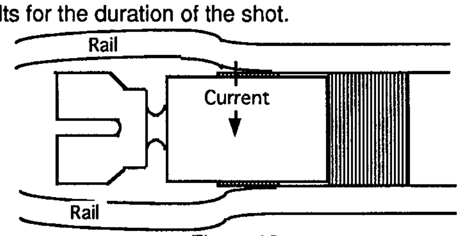

Figure 10
Launch Condition at Start-up
Current flows forward to fiber armature body

A second possibility for early time fiber conduction is the Fantail armature's inability to expand with the rails during the time of peak current. In this case the fibers would conduct until the rail separation had relaxed to the point where Fantail contact at the rear was possible.

The design attribute of reliability of the RAMBO armature should not go without mention. Although the Glidcop style Fantail armatures demonstrated superior wear over that of the aluminum, they were prone to mechanical fatigue in the web area. This fatigue resulted in the Fantail cracking in two at which time the fiber body was forced into conduction for the remainder of the shot. Had this not been the case, potential arc damage to the launcher and loss of efficiency would have resulted.

To date a high degree of operational and design experience was accumulated for the single fantail armature in conjunction with the fiber armature body of the RAMBO armature. The Single Fantail armature is being optimized at the 1.0 MA level. The launch mass is 215 grams which, for the Benet barrel, results in a 2E9 A^2-s action value. Accordingly,

the minimum web is 0.375 inches. As shown in Figure 11. the length of the trailing arm is being increased to assess the affect of the secondary trailing arm on the armature compliance.

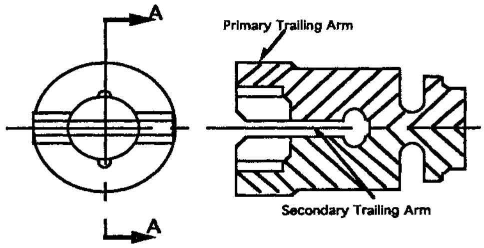

Figure 11
Modified Single Fantail Armature
Primary and Secondary Trailing Arms

Effective Trailing Arm Length: Another outgrowth of the Fantail test program is the consideration of the location of the current entry site along the length of the armature at the time of start-up. For the armature to breakaway, both the friction due to mechanical interference of the armature with the rails and the friction which arises from the induced magnetic normal force in the trailing arms has to be overcome. Equation [6] equates the driving force to the sum of the insertion force and the magnetically induced trailing arm friction.

$$\frac{L'I^2}{2} = 2\mu_s \frac{\mu I^2 L}{2\pi R} + F_{ins} \quad [6]$$

where:

I: Measured breakaway current (A)

μ_s: Static Coefficient of Friction

R: Trailing Arm Separation center to center

F_{ins}: Measured Insertion Force (N)

L:Trailing Arm Length

Solving for $\mu_s \frac{L}{R}$ as a function of $\frac{F_{ins}}{I^2}$ yields the plot of Figure 12. Given the measured insertion force and the current at which the armature first moved, the ordinate value of $\mu_s \frac{L}{R}$ can be located. Assuming a value for R and μ_s, the length of the trailing arm in conduction can be found.

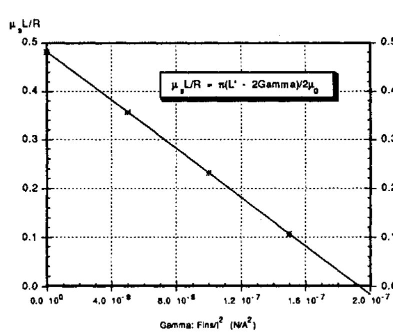

Figure 12
Gamma vs $\mu_s L/R$

Benet shot 20 had a breakaway current of 375KA and an initial insertion force of 4550 lbs (20000 N). This equates to a gamma of 1.42E-7 which yields a value of $\mu_s \frac{L}{R}$ of 0.125. For the 50mm Fantail armature:

$$25 \text{ mm} < \mathbf{R} < 50 \text{ mm}, \qquad 0.1 < \mu_s < 1$$

Therefore;

$$0.05\text{mm} < \mathbf{L} < 6.25 \text{ mm}$$

Given the physical value for the armature trailing arm length of L=1.25" (31.75mm), this range of values for L suggests that the current entered towards the front of the armature. The induced magnetic normal force is at best 20% of the the anticipated value expected for current entering at the rear of the armature. This indicates that current initially flows towards the front of the contact at the time of start-up, thereby, effectively reducing the expected normal contact force to that of the interference fit between the armature and the rail.

Conclusions

The RAMBO armature test results provided evidence that current sharing between the distributed contacts was dominated by the relative stiffness between the fiber and fantail armature sections. Aluminum armatures proved to be more compliant than Glidcop because the aluminum was comparatively less brittle. Although Glidcop armatures demonstrate a lower heat rise than there aluminum counterpart, the Glidcop web had to be made smaller than that of aluminum in oder to maintain compliance. This reduction in web dimension resulted in the fracturing of the web before any benefit to compliance could be reailzed.

The test results furthered our understanding of the importance of action in the sizing of the armature cross sectional area. The armature must be designed to meet the expected action produced by the launcher system. The launch system variables of the barrel , power supply and armature mass must be considered collectively to ensure that adequate armature cross sectional area is provided.

The assumption of cantilever beam motion in the design of the trailing arm compliance was proven to be adequate to determine the trailing deflection under load. Propoer design of the trailing arm considers both the deflection required to maintain contact in the presence of rail motion and to generate adequate contact force to prevent arcing.

This test effort addressed both issues of action and compliance. Future test efforts will focus on both the optimization of the internal trialing arm length as a function of the desired contact force and the reduction of armature wear. With a reduction in wear, a reduction in the required trailing arm deflection will ensue.

References

[1]. Halliday and Resnick, Physics. John Wiley and Sons, Inc., 1978, ch 34, pp. 751-752.